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SUPERCONDUCTIVITY AS A PROBE OF THE MAGNETIC NATURE OF TRANSITION - METAL IMPURITIES DISSOLVED IN HOST METALS*

I.M. TANG
Department of Physics, Faculty of Science, Mahidol University, Bangkok 10400, Thailand

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Abstract

The use of superconductivity to probe the magnetic nature of transition-metal (TM) impurities when they are dissolved in various host metals is reviewed. Special attention is given to the use of transport property measurments to differentiate between the TM impurities whose behaviors lie on the opposite sides of the magnetic to non-magnetic transition region. New results concerning the effect of non-magnetic TM impurities which give rise to local spin fluctuations on strong coupling anisotropic superconductors are presented.

Introduction

The magnetic (or non-magnetic) behaviours of transition-metal (TM) impurities dissolved in a host metal are determined by the interplay of the Coulomb repulsion U between the d-electrons of opposite spins which are localized about the impurity sites and the potential V which mixes the d-electrons of the impurities with the conduction electrons of the host metal. The Coulomb repulsion U gives rise to a correlation between the d-electrons of opposite spins. The correlation plays an important role in the formation of a local magnetic moment at the impurity site. The mixing potential V causes an impurity state of width $\Gamma_d = \pi N(0) V^2$ to form (N (0) being the density of states at the Fermi surface of the host). As the width of the impurity states increases, the electrons in the state begin to delocalize. This delocalization would hinder the formation of the local moment or may even lead to the suppression of the magnetic moment possibly

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present in the atomic state of the impurity atom. The conflicting roles of the Coulomb repulsion and the mixing potential in the formation of the local magnetic moments can be studied together by introducing the dimensionless parameter $g = U/\pi \Gamma_d$. In the limit g goes to infinity, a local moment would be formed at the impurity site. This limit occurs if either U goes to infinity or the width of the impurity state becomes very narrow. In the opposite limit of g going to zero, no magnetic moments are formed and the behavior of the TM impurities in the host metal is non-magnetic. The transition from non-magnetic to magnetic behavior is believed to occur somewhere around $g = 1$, the exact point being in doubt. In Table 1, I have listed the behaviors of some TM impurities when they are dissolved in different host metals. The general trend in the behaviors can be understood in terms of the interplay of U and V given above.

Three different models have been used to obtain a theoretical picture of the physics of these systems. They are the Anderson model,[1] the Wolff model[2] and the s-d model.[2] The first two are complimentary to each other. The first describes the case where the host is a simple metal while the second describes the case where the host is another transition metal. The most important term in both models is the two-body interaction term which describes the Coulomb repulsion of the d-electrons of opposite spins which are localized at the impurity sites. The s-d model describes the system after the long-lived magnetic moments have been formed. It has been shown[4] that the s-d model can be obtained from the Anderson model in the limit that the Coulomb repulsion energy in the Anderson model goes to infinity. The Kondo effect[3] arises when the interaction term in the s-d model is treated beyond the second order perturbative treatment of the Born approximation.

Since there is no exact way to treat the two-body Coulomb interactions present in a N-body system, approximate methods have to be used to study the Anderson (and Wolff) model. Some of these involve the replacement of the two-body interactions with an effective one-body interaction. Others involve the summing of selective diagrams appearing in the perturbative expansion of the propagators of the system. All of these methods suffer from the fact that many of the higher order interactions generated from the basic interaction term are neglected. No single method can be used to cover the entire range of possible magnetic (and non-magnetic) behavior of the TM impurities since many of the approximations appropriate for one region are not appropriate in another region. The lack of a single method leads to difficulties when dealing with the crossover (transition) region between the magnetic and non-magnetic behaviour regions. This is clearly indicated by the many disagreements between the theoretical predictions and the experimental observations on systems in this region. Further complicating matters are the fact that it is often difficult to determine experimentally whether a particular system belongs to one or the other side of the transition since the transition can occur with an

TABLE 1. MAGNETIC NATURE OF VARIOUS TRANSITION METAL IMPURITIES DISSOLVED IN VARIOUS HOST METALS

Host	Magnetic	Non–Magnetic
Copper Γ_d 0.3-0.4 eV.	*Cu*Mn, *Cu*Cr, *Cu*Fe *Cu*Co	CuNi
Zinc# Γ_d 0.7-1.0 eV.	*Zn*Mn, *Zn*Cr, *Zn*Fe	*Zn*Ni, *Zn*Co
Aluminium Γ_d 1.0-1.5 eV.		*Al*Mn, *Al*Cr, *Al*Fe
Palladium*	*Pd*Fe, *Pd*Mn	*Pd*Ni, *Pd*Cr, *Pd*V
Platinum*	*Pt*Mn	*Pt*Fe, *Pt*Co, *Pt*Cr *Pt*V

The zinc-3d TM impurity systems, *Zn*Mn and *Zn*Cr, exhibit both Kondo like and LSF like behaviors in different temperature regions.

For *Zn*Mn	Kondo like	$T > 0.5$ K	T_K =1 K
	LSF like	$T < 0.5$ K	T_{LSF} =4.5 + 0.5 K
For *Zn*Cr	Kondo like	$T > 0.6$ K	T_K =3 K
	LSF like	$T < 0.6$ K	T_{LSF} =2.5 + 0.5 K

*Wolff systems.

TABLE 2. THEORIES FOR SUPERCONDUCTORS CONTAINING TRANSITION METAL IMPURITIES WHOSE BEHAVIOUR BELONG TO DIFFERENT MAGNETIC REGIONS.

Magnetic	Non Magnetic
PARAMAGNETIC SYSTEMS	NON MAGNETIC SYSTEMS
SHIBA-RUSINOV THEORY[a]	ANDERSON THEORY[f]
MACHIDA THEORY[b]	NON MAGNETIC VIRTUAL BOUND STATE SYSTEMS
ABRIKOSOV-GOR'KOV THEORY[c]	SALOMAA & NIEMINEN THEORY[g]
KONDO SYSTEMS	MACHIDA & SHIBATA THEORY[h]
MÜLLER-HARTMANN & ZITTARTZ THEORY[d]	NON MAGNETIC RESONANT STATE SYSTEMS
MATSUURA, ICHINOSE & NAGAOKA THEORY[e]	KAISER THEORY[i]
LOCAL SPIN FLUCTUATION SYSTEMS	
SCHLOTTMANN THEORY[j]	

a. Ref. 19; b. Ref. 17; c. Ref. 5; d. Ref. 7; e. Ref. 8; f. Ref. 52; g. Salomaa, M.M. and Nieminen, R.M. (1979) *Z. Physik B* **35**, 15; h. Machida, K. and Shibata, F. (1972) *Prog. Theor. Phys.* **47**,(1917); i. Ref. 11; J. Ref. 9.

increase in the impurity concentration of less than one part per million.

Another cause for the experimental difficulties is that the changes in the normal state properties as the cross over is being made may be less than the thermal noise present in the measurements. To overcome the thermal noise problem, it has been suggested that one can look for the non-magnetic to magnetic transition point by looking at the effects of the TM impurities on the normal to superconducting (NS) phase transition which occurs over a temperature interval of less than 0.01 K. Since the superconducting state is strongly affected by the presense of magnetic impurities (in some systems, one part per million of magnetic impurities is sufficient to completely destroy the superconducting state), measurement of the NS phase boundaries should be an extremely sensitive means for studying the magnetic behaviors of the TM impurities.

To be able to use superconductivity as a probe of the possible magnetic behavior of the TM impurities, one would need to know how the impurities affect the NS transition. Like the situation with the TM impurities in the normal metal host, there is no single theory which can cover the whole range of behaviour of the impurities when they are dissolved into a superconductor. Instead there are many theories which are valid in each single magnetic behavior region. I have listed in Table 2 the various theories of superconductivity which are appropriate to the different regions. The NS phase boundaries for systems in which the TM impurities possess long-lived magnetic moments have been determined by Abrikosov-Gor'kov[5] (AG) and by Okabe and Nagi.[6] Müller-Hartmann and Zittarts[7] (MHZ) and Matsuura, Ichinose and Nagaoka[8] (MIN) have obtained the phase boundaries when the impurities become Kondo impurities. On the other side of the magnetic to non-magnetic transition point, Schlottmann[9] and Zuckermann[10] have determined the shape of the phase boundaries when the TM impurities give rise to local spin fluctuations (LSF). Kaiser[11] has obtained the phase boundaries for systems in which non-magnetic resonant states form at the impurity sites. Okabe and Nagi[12] have obtained the phase boundaries for the case where the impurities form virtual bound states. As an example of the phase boundaries predicted by the theories, I have shown in Figure 1, the phase boundaries of the Kondo superconductors as predicted by the MIN theory.[8] Maple[13] in a review paper has given examples of superconductors whose phase boundaries follow the predictions of the different theories. He pointed out that the fits of the data to the predicted decrease in T_c due to the various types of magnetic scattering mechanisms yielded information about the impurity states formed at the impurity sites. He gave examples of magnetically doped superconductors which followed the predictions of the AG theory, which exhibited the re-entrant behavior predicted by the MHZ theory for Kondo superconductors and whose transition temperatures decreased in the exponential manner predicted by Kaiser's theory.

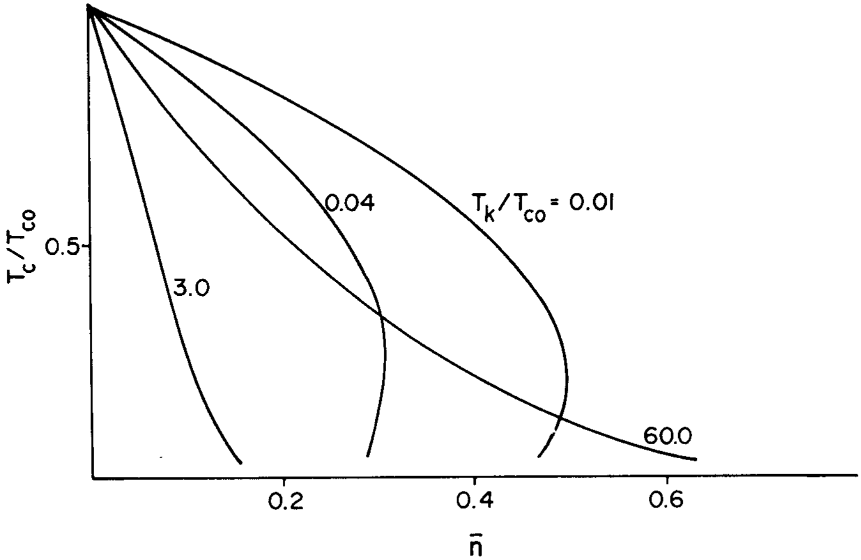

Figure 1. Decreases In The Transition Temperatures Of Kondo Superconductors As Predicted By Matsuura, Ichinose and Nagaoka Theory. The curves show the decreases as the concentration of Kondo impurities ($\bar{n}=n_i/\pi^2N(0)T_{co}$) for different values of the ratio T_K/T_{co}. The low T_K Kondo superconductors exhibit the re-entrant behavior which was the most important prediction of the theories for the Kondo superconductors. The high T_K Kondo superconductors exhibit the modified exponential decrease characteristic of non-magnetic resonant bound state impurities.

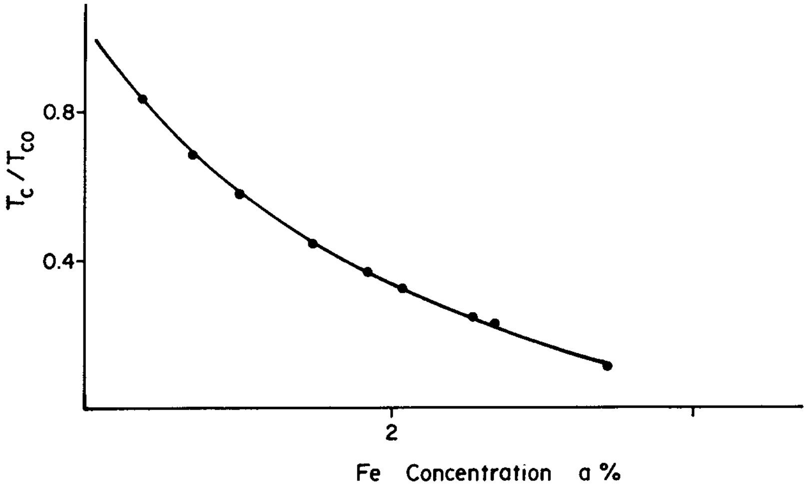

Figure 2. Decreases In The Transition Temperatures Of Ru-Fe Superconductors. The curve shows the decrease of the transition temperatures of the local spin fluctuation superconductor *Ru*-Fe. The points are the experimental points. The curve drawn through these points is the result of a numerical fit of the data to the modified exponential decrease predicted by the Kaiser theory.

Transport Properties.

Investigation of the decrease in T_c due to the impurities added to the superconductor may not, however, be sufficient to determine the magnetic nature of the TM impurities. Okabe and Nagi[6] found that the decrease in T_c due to strongly interacting paramagnetic impurities followed the same decrease predicted by the Abrikosov-Gor'kov theory for weakly interacting paramagnetic impurities. The only difference was in the definition of the pair breaking parameter. Since the pair breaking parameter is treated as a phenomenological parameter whose numerical value is determined by a fit to the experimental data, studies on the shapes of the NS phase boundaries of superconductors containing paramagnetic impurities would not be able to determine whether the impurity was a strongly interacting type or a weakly interacting type. Okabe and Nagi suggested that the specific heat jump at T_c be used to differentiate between the two since the specific heat jump of the strongly interacting system is different from that of the weakly interacting system. Since the predicted decrease in T_c of superconductors containing non-magnetic resonant states or local spin fluctuations (see Figure 2) is similar to that of the high T_K Kondo superconductors (see Figure 1), studies on the shape of the NS phase boundaries would not be able to differentiate between these two types of systems which lie on the opposite side of the magnetic to non-magnetic transition point. Many systems close to the transition point exhibit both Kondo like and LSF like behaviour. For example, the dilute *Zn*Mn systems[14] exhibit Kondo like behavior above 0.5 K with a T_K of 1 K and LSF like behavior below 0.5 K with T_{LSF} of 4.5 K. Similar behavior is seen in *Cr*Mn with the change over at 0.6 K.

It has been suggested that measurements of the transport properties of the doped superconductors would offer direct means for investigating the magnetic nature of the impurities. Work along these lines was started long ago. Kadanoff and Fal'ko[15] and Ambegaokae and Griffin[16] have studied the changes in the ultrasonic attenuation coefficient and thermal conductivity, respectively, of superconductors containing paramagnetic impurities using the Abrikosov-Gor'kov treatment of the spin flip scattering. Machida[17] and Leon and Nagi[18] have obtained expressions for the attenuation coefficients for the superconductors containing the paramagnetic impurities within the framework of the Shiba-Rusinov theory[19] for strong spin flip scattering. Matsui and Masuda[20] have carried out a computer study of the transport properties of low T_K Kondo superconductors. Recently, I have analyzed the thermal conductivity data[21] and transverse ultrasonic attenuation data[22] for the dilute *Zn*Mn superconductors in terms of a LSF description of the Mn impurities and in terms of a high T_K Kondo description of the impurities. I found[23] that while both the LSF based and high T_K Kondo based (based on the MIN theory) transverse attenuation coefficients provided for a qualitative explanation of the data, only the LSF based coefficient was able to fit the data of Lou and Bömmel[22] with reasonable values for the parameters appearing in the coefficient (see Figure 3a.). In another paper,[24] I found that the LSF based expression for the thermal conductivity could fit the data of Sanchez[21] for the dilute *Zn*Mn superconductors. I do not expect that the thermal conductivity data could be fitted to the high T_K Kondo based expression[25] using reasonable values for the parameters appearing in the expression. In addition to the above transport properties, I have also obtained expressions for the longitudinal ultrasonic attenuation whithin the framework of Schlottmann's theory for the LSF in superconductors[26] and within the framework of the MIN theory for the Kondo effect[27]. In ref. 26, I also obtained the attenuation coefficient for the case where the TM impurities form into non-magnetic resonant states. I showed that the behavior of the attenuation coefficient for the case of non-magnetic resonant states passed into the behaviour predicted for the case of LSF's as the value of the dimensionless parameter g increases. This is expected since the non-magnetic resonant states are the precusors of the LSF.

Continuing my investigation into the effects of TM impurities when their behavior lies close to the magnetic to non-magnetic transition region, I have recently obtained expressions for the nuclear spin lattice relaxation rate[28] and electromagnetic absorption rate[29] in the gapless states of the high T_K Kondo superconductors using the the MIN theory as the basis for the description of the Kondo effect. To give an indication as to how I obtained the expressions for the various transport properties, I will briefly outline how I obtained the electromagnetic absorption rate of a high T_K Kondo superconductor. I started by first expressing the absorption rate in terms of the generalized susceptibility function $\chi(\bar{q}, \omega_0)$, i.e.,

$$W(\bar{q}, \omega_0) = \tfrac{1}{2} V \omega_0 E^2 \operatorname{Im} \chi(\bar{q}, \omega_0) \tag{1}$$

where $\bar{q}$ and ω_0 are the wave vector and frequency of the absorbed radiation, respectively, and where the generalized susceptibility function (defined in the complex ω_0 - plane) is given by

$$\chi(\bar{q}, i\omega_o) = K_B T \int \frac{d^3p}{(2\pi)}{}^{3} \frac{1}{2} \quad {}_{\omega_n} \operatorname{Tr} \quad G(p, i\omega_n) G\, \Gamma(\bar{p}+\bar{q}, i\omega_n + i\omega_o)\, G(\bar{p}+\bar{q}, i\omega_n + i\omega_o) \Big\} \tag{2}$$

with $G(\bar{p}, i\omega_n)$ being the superconducting propagators written in the Nambu four space and $\Gamma(x, y)$ being the vertex corrections due to electron polarization processes and bare Coulomb interactions. The vertex corrections lead to the BCS coupling constant λ to be modified, i.e., $\lambda \rightarrow \lambda/\varepsilon$ where ε is the static dielectric constant. In the new Nambu four space (where the BCS coupling constant is λ/ε), the susceptibility function becomes

$$\chi(\bar{q}, i\omega_o) = K_B T \int \frac{d^3p}{(2\pi)}{}^{3} \frac{1}{2} \sum_{\sigma} \sum_{\omega_n} \Big\{ G_\sigma(p, i\omega_n) G_\sigma(\bar{p}+\bar{q}, i\omega_n + i\omega_o) + F_\sigma(\bar{p}, i\omega_n) F_{-\sigma}(\bar{p}+\bar{q}, i\omega_n + i\omega_o) \Big\} \tag{3}$$

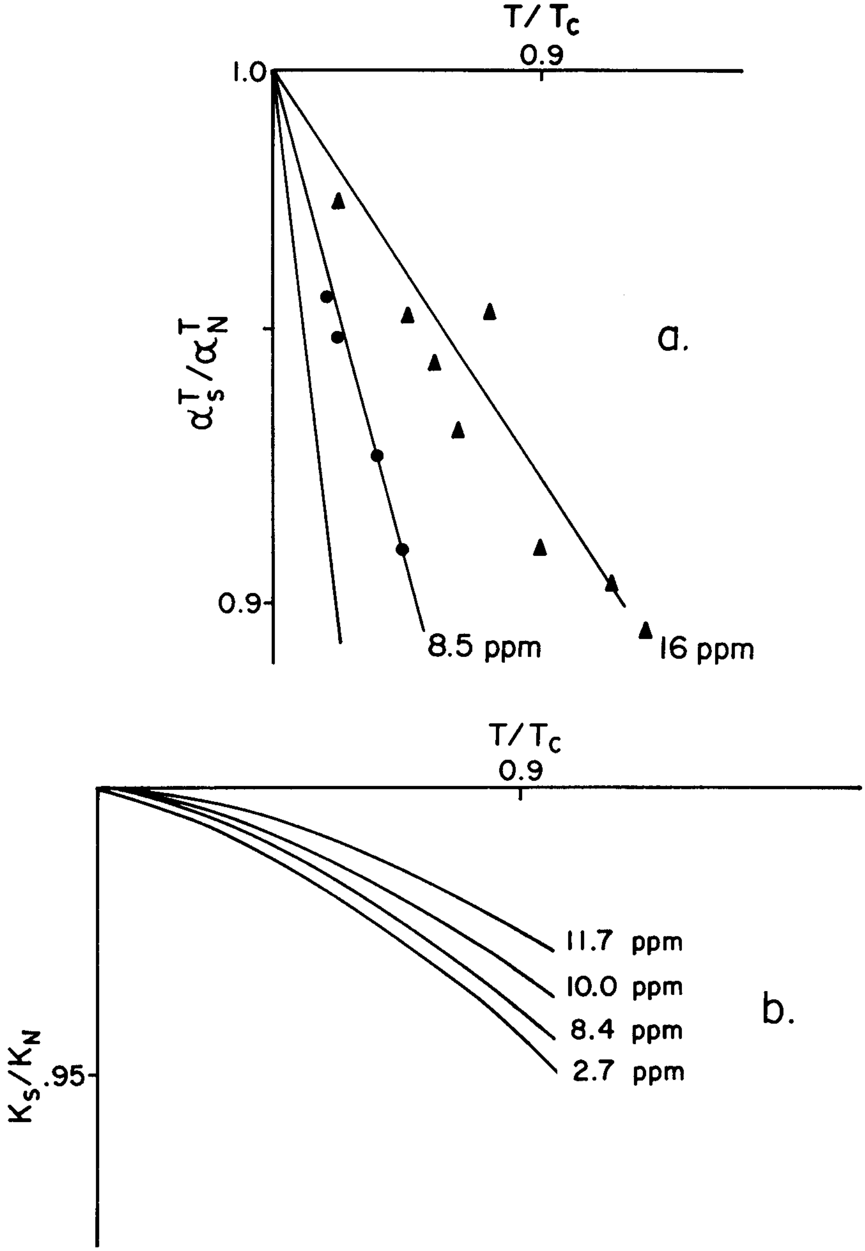

Figure 3. Fits Of The Numerical Data On The Transverse Attenuation Coefficients And Thermal Conductivity Of Dilute *Zn*Mn Superconductors To Transport Expressions Obtained On The Basis Of The Local Spin Fluctuations Description Of The Mn Impurities. a). The curves show the fits to the 8.5 ppm and 16.0 ppm Mn impurities specimens data on the transverse attenuation coefficients of Lou and Bömmel[22]; b). The curves show the fits to the thermal conductivity data of Sanchez[21].

where G_{ε} $(\bar{p}, i\,\omega_n)$ and F_{ε} $(\bar{p}, i\,\omega_n)$ are the normal and anomalous propagators in the new space. In the presence of impurities, the superconducting propagators appearing in eqn. (3) have to be replaced by the renormalized propagators which incorporate the effects of the Kondo scattering through a set of renormalization equations for the frequency and energy gap. Due to the complex nature of these equations and of eqn. (3), the susceptibility function would in general have to be evaluated numerically in the manner done by Matsui and Masuda.[20]

I found that I could obtain analytical expressions for eqn. (3) and the other transport properties if I set the temperature to be close to T_c or if I imposed an external magnetic field on the system. In both situations, it would then be possible to expand the propagators in powers of the order parameter (energy gap) and in terms of the propagators of the normal metal. The effects of the Kondo scattering could then be incorporated by making the following substitutions at all the proper vertices appearing in

$$\frac{\Upsilon(\omega_n)}{|\tilde{\omega}_n|} = \frac{1}{(1+n_i/4T^{K}N(O))\,|\omega_n| + \Gamma_{tr}V^2q^2/6}\left[1-\frac{n_i}{4T_K N^2(0)}\left[\frac{4T_K}{\pi}\right]^2\frac{1}{(|\omega_n| + 4T_K/\pi)}{}^{2}\right] \quad (4)$$

the expanded form of the susceptibility function. The absorption rate could be obtained through the definition, eqn. (1), after the function $\chi(q, i\,w_0)$ is analytically continued back to the real axis. To obtain the analytical expressions for the other transport properties, I started with relevant Kubo formula for the properties.[30]

In addition to the above work, I and a coworker have considered the problem of the Kondo impurities dissolved in transition-metal superconductors. In one paper,[31] we looked at the case where the BCS coupling was only between the d-electrons of the host metal. To solve this problem, we had to solve a set of coupled Bethe-Salpeter equations. In a second paper,[32] we looked at the case where the electron-phonon coupling existed between all the electrons in the transition metal. For this paper, we used the Suhl-Matthais-Walker[33] two band model of superconductivity. This latter paper was a continuation of some work I had done some fifteen years ago[34] on the transport properities of two band (transition metal) superconductors.

Proximity Effect Sandwiches

The main obstacle to the general use of superconductivity to probe the behavior of the TM impurities dissolved in various host metals is the fact that most systems are not superconducting. To overcome this obstacle, Kaiser[35] pointed out that the proximity effect can be used to induce superconductivity into non-superconducting host metals such as copper. Though Kaiser and Zuckermann[36] showed long ago that paramagnetic impurities dissolved in the normal (N) side of the proximity effect sandwiches could suppress the superconductivity on the superconducting (S) side of the junction, Kaiser was the first to realize that the proximity effect could be used to obtain additional systems for which superconductivity could be used to probe the nature of the magnetic state of the TM impurities dissolved in the host metal. He pointed, in particular, to the use of the proximity effect to obtain new Kondo superconductors. His theory was able to account for the behaviors of the superconducting states of the Kondo systems, *Cu*Cr, *Cu*Mn and *Cu*Co[37]. Jacobsen *et al.*[38], used Kaiser's theory to obtain information about the magnetic nature of Mn dissolved in Ag and of Fe dissolved in Au. Kaiser's theory is based on the MHZ treatment of the Kondo effect. Yoksan[39] has restudied the proximity effect tunneling into Kondo alloys using the MIN theory to describe the Kondo effect. He found that for the low T_k Kondo impurities, the results based on the MIN theory are the same as those obtained by Kaiser.

The present author began a systematic investigation of the proximity effect tunneling into normal layers containing TM impurities whose behaviors lie in the different magnetic behavior region. Like Kaiser, I assumed that the superconducting layer can be described by the Bardeen-Cooper-Schrieffer[40] (BCS) hamiltonian; the normal layer, by the Anderson hamiltonian[1] and that the tunneling can be described by the McMillian tunneling hamiltonian.[41] The effects of the TM impurities in the different magnetic behavior regions were obtained by using the d-electron propagators appropriate to the different regions in the calculations of the self energy corrections of the N-layer electrons due to the TM impurities. In this way, I was able to obtain theories for the proximity effect sandwiches when the TM impurities form into non-magnetic resonant states[42], virtual bound states[43], non-magnetic impurity states which give rise to LSF[44,45], Kondo impurities[46], and into strongly interacting paramagnetic states[47]. In each of these papers, the d-electron propagators were the ones appropriate to the relevant theories listed in Table 2. The differences between my work on the Kondo superconductors and that of Kaiser[35] and of Yoksan[39] are due to my use of the MIN theory and to my concern with high T_K Kondo impurities. As an example of the decrease in T_c of the proximity effect sandwiches which I have obtained, I have shown on Figure 4, the decrease in T_c of sandwiches containing LSF's as functions of the thickness of the N layer for several values of the dimensionless parameter g. As is seen, the decrease in T_c for the lower values of g follows the modified exponential decay typical of non-magnetic impurities. The curve for $g=1$, however, is similar to those obtained by Kaiser and Zuckermann[36] for proximity effect sandwiches containing weakly interacting paramagnetic impurities. Finally, I would like to mention my study on the proximity effect tunneling into two band metals containing Kondo impurities[48].

Final Remarks.

All of the theoretical studies mentioned in the previous sections are based on the Bardeen-Cooper-Schrieffer[40] theory of superconductivity. Since the electron-phonon coupling in this model is assumed to be weak, the contribution of the electron-phonon interaction

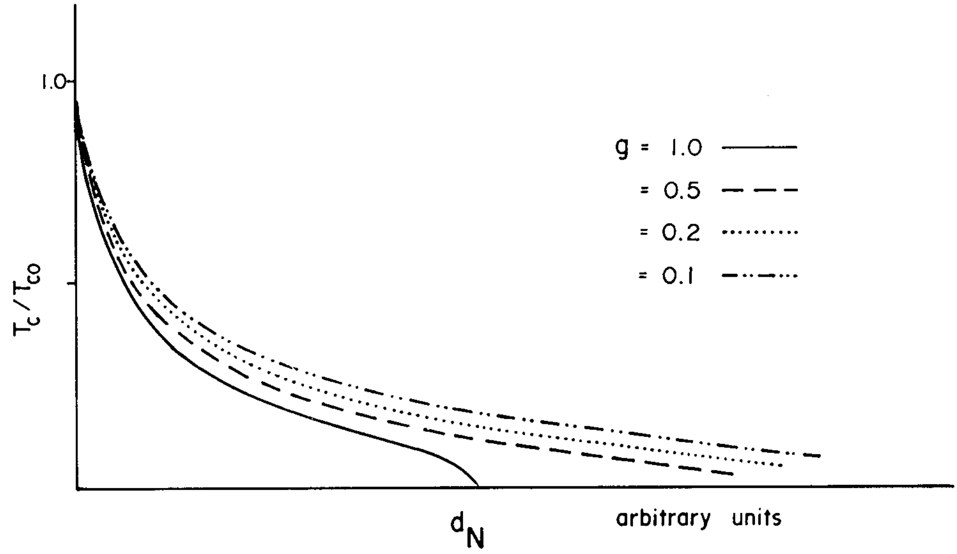

Figure 4. Decrease In The Transition Temperatures Of Proximity Effect Sandwiches Containing Local Spin Fluctuations In The Normal Layer. The curves show the decreases as the thickness of the normal layer is increased for different values of g. The lower values of g moves the TM impurities closer to the non-magnetic resonant bound state behavior region. The higher values of g moves the TM impurities closer to the magnetic behavior region. The multiplicative renormalization method used in the Schlottmann[9] theory is used to obtain the behavior of the TM impurities dissolved in the normal layer.

to the diagonal part of the self energy correction is ignored. The rather large electron-phonon mass-enhancement seen in certain metals points to the need to take into consideration the corrections to the diagonal part of the self energy due to the electron-phonon interaction when formulating a theory of superconductivity for these metals. The Eliashberg theory[49] which is an extension of the Migdal theory[50] for the electron-phonon interaction in normal metals treats explicitly the electron-phonon interactions and the Coulomb repulsion between the electrons belonging to the Cooper pair while calculating both the diagonal and off-diagonal part of the self energy corrections. Using the Eliashberg theory, Carbotte and coworkers[51] have been able to calculate the transition temperatures of several strong coupling superconductors with only information about the normal phases of the metals. The BCS theory also assumes that the Fermi surface of the metal is spherical and that the electron-phonon coupling constant is constant over the surface of the Fermi sphere, i.e. the coupling constant is isotropic. The Fermi surfaces of real metals are known, however, to be highly anisotropic. The importance of this anisotropy to superconductivity has been long recognized. Anderson[52] showed this when he considered the effects of normal impurity scattering on the T_c's of anisotropic superconductors. Unlike the case of isotropic superconductors where the normal scattering by non magnetic impurities does not lead to any change in T_c, the normal scattering in anisotropic superconductors can lead to decreases in T_c through the washing out of the anisotropy. This finding was used to explain the decreases in T_c of superconducting aluminium observed when small amounts of non-magnetic impurities were added to the aluminium.

The effects of magnetic impurities on anisotropic and strong coupling superconductors have been and are now being investigated. Markowitz and Kadanoff[53] studied the effects of paramagnetic impurities on weak coupling (WC) anisotropic superconductors within the framework of the AG treatment of the spin flip scattering. Okabe and Nagi[54] and Yoksan and Nagi[55] have looked at the effects of strongly interacting paramagnetic impurities on the WC anisotropic superconductors using the SR theory. Recently, Yoksan[56] obtained expressions for the decrease in T_c of the WC anisotropic superconductor due to scattering by Kondo impurities. Schachinger *et al.*[57] and Allen and Mitrovic[58] have investigated the effects of paramagnetic impurities on strong coupling (SC) isotropic superconductors within the framework of the AG theory. Yoksan and Nagi[59] studied the effects of Kondo impurities on the SC isotropic superconductors. Daams *et al.*[60] have studied the effects of the paramagnetic impurities on the SC anisotropic superconductors within the framework of the AG theory. Schachinger[61] and Yoksan and Nagi[62] looked at the effects of strongly interacting paramagnetic impurities on the SC anisotropic superconductors using the SR theory.

The present author has begun a series of studies on the effects of LSF's on superconductors which are either anisotropic or strong coupling or both. For the WC anisotropic superconductors, I found that the LSF's lead to a reduction in the anisotropy parameter $\langle a^2 \rangle$ given by

$$\langle a^2\rangle_{\mathrm{red}} = \langle a^2\rangle(1-\mu_{\mathrm{eff}}\triangle\psi), \tag{5}$$

with

$$\triangle\psi = \delta\psi/[1+n_iN_d(O)/N(O)]$$

$$\delta\psi = n_i\left[\frac{N_d(O)}{N(O)}\right]\frac{\Gamma_d}{2\pi T\{1+n_i[N_d(O)/N(O)]\}}\left[\psi\left[\frac{1}{2}\right]-\psi\left[\frac{1}{2}+\frac{\omega_D}{2\pi T}\right]\right]$$

and an increase in the Coulomb repulsion between the electrons in the Cooper pair

$$\mu_{\mathrm{eff}} = \mu + n_i\left[\frac{N_d(O)}{N(O)}\right]U_{\mathrm{eff}}\,\chi(O) \tag{6}$$

The transition temperature of the WC anisotropic superconductor which contained LSF's was found to be given by

$$T_c/T_{cO}=\exp\left[-\left[\frac{n_i}{N(O)g^*_{eff}}\;\frac{\left[\frac{N_d(O)}{N(O)}\right]\left[1+\frac{U_{eff}\,\chi(O.}{N(O)g^*_{eff}}\left[1+N(O)V_{e\text{-}ph}<a_2>\delta\right]\right]+N(O)V_{e\text{-}ph}<a_2>\delta}{1-n_i\left[\frac{N_d(O)}{N(O)}\right]\frac{U_{eff}\,\chi(O.}{N(O)g^*_{eff}}\left\{1+N(O)V_{e\text{-}ph}<a_2>\delta\right]}\right]\right] \tag{7}$$

where

$$N(O)g^*_{eff}=N(O)V_{e\text{-}ph}\,(1+<a_2>)-\mu$$

where T_c^0 is the transition temperature of the isotropic superconductor containing the same impurities. For the isotropic SC superconductor containing LSF's, I obtained

$$\frac{T_c^{SC}}{T_{co}^{SC}}=\exp-\left\{\frac{1+\lambda}{\lambda-\mu_{eff}}\,n_i\left[\frac{N_d(O)}{N(O)}\right]\frac{\frac{1}{1+\lambda}+\frac{1}{\lambda-\mu_{eff}}\;U_{eff}\,\chi(O)}{1-n_i\,\frac{1}{\lambda-\mu_{eff}}\left[\frac{N_d(O)}{N(O)}\right]U_{eff}\,\chi(O)}\right\} \tag{8}$$

where T_{co}^{SC} is the transition temperature of the pure SC superconductor. Work is still in progress regarding the SC anisotropic superconductors which contain LSF's. In the above expressions, $\chi(o)$ is the static susceptibility due to rapid spin fluctuations and U_{eff} is the effective Coulomb pseudo potential encountered first in Kaiser's theory for non-magnetic resonant states[11] and then in Schlottmann's theory for the LSF's.[9]

I have also been investigating the effects of non-magnetic resonant states on the strong coupling anisotropic superconductors. I found that the strong coupling expression for T_c could not be obtained by simply replacing the anisotropy parameter $<a^2>$ in the weak coupling expression by the energy gap anisotropy parameter

$$<\alpha^2>=\frac{\lambda^2(1+\mu_{eff})^2}{(1+\lambda)^2(\lambda-\mu_{eff})^2}<a^2> \tag{9}$$

This simple equivalence between the two expressions for T_c is true if only normal scattering occurs or if the spin flip scattering by magnetic impurities is treated within the AG second order treatment. Blezius and Carbotte[63] were the first to point out that the two expressions (the SC and WC) may not be connected in a simple manner. Comparing the expressions for T_c of superconductors containing strongly interacting paramagnetic impurities obtained by Okabe and Nagi[54] and by Yoksan and Nagi,[62] I find that the SC expression of Yoksan and Nagi contains a term which has no counterpart in the WC expression of Okabe and Nagi. My SC expression also contains a term which has no counterpart in my WC expression. The details of the calculations leading to eqns. (5) to (9) have been submitted for publication elsewhere.

References:

1. Anderson, P.W. (1961) *Phys. Rev.* **124**, 41.
2. Wolff, P.A. (1961) *Phys. Rev.* **124**, 1030.
3. Kondo, J. (1964) *Prog. Theor. Phys.* **32**. 37.
4. Schrieffer, J.R. and Wolff, P.A. (1966) *Phys. Rev.* **149**, 491.
5. Abrikosov, A.A. and Gor'kov, L.P. (1961) *Sov. Phys.-JETP* **12**, 1243.
6. Okabe, Y. and Nagi, A.D.S. (1983) *Phys. Rev. B* **28**, 1320.
7. Müller-Hartmann, E. and Zittartz, J. (1971) *Phys. Rev. Letters* **26**, 428.
8. Matsuura, T., Ichinose, S. and Nagaoka, Y. (1977) *Prog. Theor. Phys.* **53**, 1286.
9. Schlottmann, P. (1977) *Sol. State Comm.* **21**, 663.
10. Zuckermann, M.J. (1970) *J. Phys. C* **3**, 2130.
11. Kaiser, A.B. (1970) *J. Phys. C* **3**, 410.
12. Okabe, Y. and Nagi, A.D.S. (1983) *Phys. Rev. B* **28**, 2455.
13. Maple, M.B., (1972) *AIP Conf. Proc. No. 4,* Douglass, D.H, AIP, New York, p.175.
14. Ford, P.J., Rizzuto, C. and Salamoni, E. (1972) *Phys. Rev. B* **6**, 1851.
15. Kadanoff, L.P. and Fal'ko, I.I. (1964) *Phys. Rev.* **136**, A1170.
16. Ambegaokar, V. and Griffin, A. (1965) *Phys. Rev.* **137**, A1151.
17. Machida, K., (1975) *Prog. Theor. Phys.* **54**, 1251.
18. Leon, B. and Nagi, A.D.S. (1974) *J. Phys. F* **4**, L13.
19. Shiba, H., (1968) Prog. Theor. Phys. *40,* 435; Rusinov, A.I. (1969) *Sov. Phys.-JETP* **29**, 1101.
20. Matsui, K. and Masuda, Y. (1979) *J. Phys. Soc. Japan* **46**, 1444.
21. Sanchez, D.H. (1974) *J. Low Temp. Phys.* **17**, 101.
22. Lou, D.Y. and Bömmel, H.E. (1974) *Phys. Rev. B* **9**, 3739.
23. Tang, I.M. (1986) *Phys. Rev. B.* In press.
24. Tang, I.M. (1985) *Phys. Letters* **111A**, 60.
25. Tang, I.M. (1985) *J. Low Temp. Phys.* **60**, 263.
26. Tang, I.M. (1985) *J. Low Temp. Phys.* **60**, 9.
27. Tang, I.M. (1985) *J. Low Temp. Phys.* **59**, 517.
28. Tang, I.M. (1985) *J. Low Temp. Phys.* **61**, 309.
29. Tang, I.M. and Chollatharnat, S. (1985) Poster A5 presented at *11th Conference Science and Technology Thailand,* 24-26 October 1985, Bangkok, Thailand.
30. Maki, K. (1969) in *Superconductivity Vol. II,* ed. Parks, R.D., Dekker, New York, chap. 13.
31. Tang, I.M. and Roongkeadsakoon, S. (1982) *Phys. Letters* **92A**, 349.
32. Tang, I.M. and Roongkeadsakoon, S. (1984) *J. Low Temp. Phys.* **55**, 411.
33. Suhl, H., Matthais, B.T. and Walker, L.P. (1959) *Phys. Rev. Letters* **3**, 552.

34. Tang, I.M. (1970) *Phys. Rev. B* **2**, 129; Nusair, M. and Tang, I.M. (1974) *Phys. Rev. B* **10**, 308.
35. Kaiser, A.B. (1980) *Phys. Rev. B* **22**, 2323.
36. Kaiser, A.B. and Zuckermann, M.J. (1970) *Phys. Rev. B* **1**, 229.
37. Dumoulin, L., Guyon, E. and Nedellec, P. (1977) *Phys. Rev. B* **16**, 1086.
38. Jacobsen, N., Hansen, M. and Claeson, T. (1982) *Z. Physik B* **46**, 45.
39. Yoksan, S. (1982) *J. Low Temp. Phys.* **49**, 33.
40. Bardeen, J., Cooper, L.N. and Schrieffer, J.R. (1957) *Phys. Rev.* **103**, 1175.
41. McMillian, W.L. (1968) *Phys. Rev.* **175**, 537.
42. Tang, I.M. and Roongkeadsakoon, S. (1984) *J. Low Temp. Phys.* **54**, 27.
43. Tang, I.M. and Roongkeadsakoon, S. (1984) *J. Low Temp. Phys.* **56**, 531.
44. Tang, I.M. and Roongkeadsakoon, S. (1984) *J. Low Temp. Phys.* **56**, 441.
45. Tang, I.M. and Ratanapun, S. (1985) *J. Low Temp. Phys.* **59**, 383.
46. Tang, I.M. (1984) *J. Low Temp. Phys.* **57**, 189.
47. Tang, I.M., Roongkeadsakoon, S. and Ratanapun, S. (1984) *J. Low Temp. Phys.* **57**, 151.
48. Tang, I.M. and Roongkeadsakoon, S. (1983) *J. Low Temp. Phys.* **51**, 67.
49. Eliashberg, G.M. (1960) *Sov. Phys.-JETP* **11**, 696.
50. Migdal, A.B. (1958) *Sov. Phys.-JETP* **7**, 996.
51. Daams, J. and Carbotte, J.P., (1980) *J. Low Temp. Phys.* **46**, 135; Baquero, R. and Carbotte, J.P., (1983) *J. Low Temp. Phys.* **51**, 135; Daams, J., Carbotte, J.P., Ashraf, M. and Baquero, R. (1984). *J. Low Temp. Phys.* **55**. 1.
52. Anderson, P.W. (1959) *J. Phys. Chem. Solids* **11**, 26.
53. Markowitz, D. and Kadanoff, L.P. (1963) *Phys. Rev.* **131**, 563.
54. Okabe, Y. and Nagi, A.D.S. (1983) *Phys. Rev. B* **28**, 1323.
55. Yoksan, S. and Nagi, A.D.S. (1984) *Phys. Rev. B* **30**, 2917.
56. Yoksan, S. (1984) *Sol. State Comm.* **51**, 175.
57. Schachinger, E., Daams, J.M. and Carbotte, J.P. (1980) *Phys. Rev. B* **22**, 3194.
58. Allen, P.B. and Mitrovic, B. (1982) In *Solid State Physics Vol. 37*, eds. by Ehrenreich, H. Seitz F. and Turnbull D., Academic Press, New York, P.1.
59. Yoksan, S. and Nagi, A.D.S. (1984) *J. Low Temp. Phys.* **56**, 13.
60. Daams, J.M., Schachinger, E. and Carbotte, J.P. (1981) *J. Low Temp. Phys.* **42**, 69.
61. Schachinger, E. (1982) *Z. Physik B* **47**, 217; Schachinger, E. Carbotte, J.P. (1984) *Phys. Rev. B* **29**, 165.
62. Yoksan, S. and Nagi, A.D.S. (1984) *Phys. Rev. B* **30**, 2659.
63. Blezius, J.W. and Carbotte, J.P. (1984) *Can. J. Phys.* **62**, 158.

บทคัดย่อ

บทความนี้ส่วนใหญ่มาจากบทความการบรรยายพิเศษที่ได้รับเชิญให้บรรยายต่อที่ประชุมวิชาการวิทยาศาสตร์และเทคโนโลยีแห่งประเทศไทย ครั้งที่ 11 เมื่อวันที่ 24-26 ตุลาคม 2528 ที่กรุงเทพฯ ประเทศไทย โดยจะได้กล่าวถึงการใช้ตัวนำยิ่งยวดเป็นหัววัดความเป็นแม่เหล็กตามธรรมชาติของสิ่งเจือปนโลหะทรานซิเชิ่น (TM) เมื่อได้ละลายซึมเข้าไปในโลหะที่เป็นฐานหลักชนิดต่าง ๆ กัน เฉพาะอย่างยิ่งจะเน้นหนักถึงการศึกษาคุณสมบัติการซึมผ่านของสิ่งเจือปน TM ว่าสิ่งเจือปนนี้จะประพฤติตัวเป็นสารแม่เหล็กหรือไม่ใช่สารแม่เหล็ก นอกจากนั้นจะบรรยายถึงผลการคำนวณใหม่ ๆ เกี่ยวกับผลของสิ่งเจือปน T.M. ซึ่งไม่เป็นสารแม่เหล็ก ทำให้เกิดการรบกวนสปินในบริเวณใกล้เคียงของตัวนำยิ่งยวดที่เป็นแอนไอโซโทรปิคและมีการคับปลิ้งอย่างแรง